A *ROSAT* Bright Source Catalog Survey with the *Swift* Satellite

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ABSTRACT

We consider the prospects for a complete survey of the 18,811 sources of the *ROSAT* All-Sky Survey Bright Source Catalog (BSC) with NASA's *Swift* gamma-ray burst (GRB) mission. By observing each BSC source for 500 s with the satellite's imaging X-ray and UV/optical telescopes, this "Swift Bright (Source) Catalog Survey" (Swift-BCS) would derive $<5''$ source positions for all BSC sources that have not faded substantially from their *ROSAT*-era flux levels, and provide 0.2–10 keV X-ray and UV or optical flux measurements. The improvement by a factor of 10 to 30 in the two-dimensional localization for these sources will enable optical identifications or deep limits in nearly every case, fulfilling the promise of the BSC as a multiwavelength catalog, and allowing the full enumeration of its rare source populations. Since the Swift-BCS can be accomplished with 10% of the time on-orbit, for a three-year mission, and since its targets will be of lower priority than active afterglows, it will not conflict with the primary *Swift* mission of GRB follow-up observations. Moreover, the BSC targets can be scheduled so as to advance the secondary goals of *Swift*: Daily monitoring of the full sky in the hard X-ray band (source fluxes of $\gtrsim$20 mCrab, 10–100 keV) with the wide-field Burst Alert Telescope (BAT); and a two-year all-sky BAT survey down to $\gtrsim$1 mCrab. The resulting expansion of the catalog of identified X-ray sources from 2000 to 18,000 will provide a greatly-enriched set of targets for observation by *XMM-Newton*, *Chandra*, and future high-energy observatories.

Subject headings: surveys — X-rays: general — ultraviolet: general

1. Introduction

NASA's *Swift* Midex mission is in its final ground-based testing phases and is scheduled for launch in September 2004[1]. Designed for and dedicated to the detection and automated

[1] *Swift* mission web site: `http://swift.gsfc.nasa.gov/`

follow-up of gamma-ray bursts (GRBs), *Swift* has a broad-band complement of instruments: a coded-mask CdZnTe Burst Alert Telescope (BAT; Barthelmy 2000) to localize the prompt hard X-ray emission of gamma-ray bursts, and for pointed observations of the subsequent GRB afterglows, a nested-mirror grazing-incidence X-ray telescope (XRT; Burrows et al. 2003) and a UV/Optical telescope (UVOT; Roming et al. 2000) which is a slightly-modified version of the Optical Monitor on *XMM-Newton* (Mason et al. 2001). The XRT, with an EPIC MOS CCD as its focal plane detector, has an effective area of 135 cm^2 at 1.5 keV, making it the seventh-largest focusing X-ray telescope ever flown – including the three telescopes on *XMM* – and its 18$''$ (half-power diameter) point-spread function compares favorably with all previous missions except the *Einstein* and *ROSAT* HRI instruments, *Chandra*, and *XMM*. The UVOT provides UV/optical (200 nm to 600 nm, depending on the filter) sensitivity over most of the field-of-view of the XRT, and can reach $B = 24$ mag in a 1000 s exposure.

Uniquely among missions of its size, *Swift* possesses large reaction wheels which give it a slew rate of one degree per second, enabling prompt follow-up of GRB positions and a continuous sequence of pointings over the course of each orbit, scheduled so that the narrow-field instruments (XRT and UVOT) are never Earth-occulted. In combination, as we explore below, these capabilities make it attractive and feasible to execute a complete *Swift* survey of the *ROSAT* Bright Source Catalog.

The *ROSAT* All-Sky Survey (RASS) Bright Source Catalog (BSC; Voges et al. 1999) contains 18,811 sources, covering 92% of the sky, down to count rates of 0.05 PSPC c s^{-1}, corresponding to a flux limit of roughly 7×10^{-14} erg cm s^{-1} (0.5–2.0 keV) for an unabsorbed blackbody spectrum with $kT = 0.1$ keV. It is the most sensitive X-ray all-sky survey ever performed, reaching fluxes 100 times fainter than the *Einstein* survey, and with a greater emphasis on the soft X-ray band. Typical flux-dependent positional uncertainties for BSC sources are 10–20$''$ (radius, one-sigma).

These positional uncertainties are large enough that they have prevented confident optical identification – and hence, physical classification – of the great majority of BSC sources. Firm identifications have been derived for a subset of roughly 2000 of the brightest sources by the *ROSAT* Bright Survey group (Fischer et al. 1998; Schwope et al. 2000). Suggested identifications have been proposed for perhaps 4000 more in wide-area optical surveys (Zickgraf et al. 2003; Anderson et al. 2003), but the confidence level of these is such that most have not been subject to subsequent follow-up observations.

Among the $\gtrsim$12,000 unidentified BSC sources that remain there must exist, undiscovered and in quantity, members of rare and interesting X-ray source populations; members of common source populations that exhibit distinctive features making them worthy of further study; and quite possibly, entirely new classes of Galactic or extragalactic X-ray source that

have so far escaped notice.

These rare and interesting source populations are best identified from within the BSC rather than by other methods, for at least two reasons. First, any BSC source has a sufficiently high X-ray flux to permit detailed follow-up observations by *XMM*, *Chandra*, and future high-energy missions. Second, as we discuss below, the optical counterparts of BSC sources are bright enough, in most cases, to be accessible to optical spectroscopy from modest-sized (4-m class) facilities, which will allow extensive ground-based exploration of the physical properties of the sources.

In the sections that follow, we make the case for a complete survey of BSC sources with *Swift*, the Swift-BCS. With a 500-s pointing on each source, sources near the brightness threshold of the BSC will be re-detected with 25 counts in the *Swift* XRT, yielding a $<5''$ position from the X-rays alone. The simultaneous 500-s UVOT exposure will have a detection limit of $B = 23.5$ in the B-filter, with comparable limits in other UV/optical filters when they are used. In most cases this combination of observations will enable the identification of a unique UV/optical counterpart for the source, allowing flux estimates or upper limits for the source to be derived from archival surveys spanning the electromagnetic spectrum. In all, the required 9.4 Msec of observations can be accomplished with 10% of the time on-orbit over a three-year portion of the *Swift* mission. It will thus be possible to schedule Swift-BCS observations so as to advance the secondary goals of the mission: Daily monitoring of the full sky to fluxes of $\gtrsim$20 mCrab (10–100 keV) with the BAT, and a two-year all-sky BAT survey to $\gtrsim$1 mCrab.

2. Fulfilling the Promise of the BSC

In this section we show how deriving a uniform set of $<5''$ precision source localizations for the sources of the BSC will fulfill the promise of the BSC as a multiwavelength catalog of the 18,811 brightest soft X-ray sources in the sky. In addition, we discuss past and current efforts at BSC source identification, and outline some of the returns that near-complete BSC identification will enable.

2.1. BSC Optical Counterparts

The identification of optical counterparts for every BSC source, or the establishment of constraining upper limits, is the crucial enabling step that will convert the BSC from an X-ray source catalog into a multiwavelength catalog which – by comparison to large-area

off-band surveys – can present the X-ray, optical, near-infrared, and (in many cases) radio properties of those same X-ray sources.

Most known types of X-ray sources in the BSC will have optical counterparts that are bright enough to have been detected in the Palomar All-Sky Surveys and to be listed in the resulting USNO[2] and DPOSS[3] catalogs. Such sources will also be accessible to optical-spectroscopic investigation from modest-sized ground-based facilities. At the limiting BSC count rate of 0.05 PSPC c s^{-1}, the expected source B-band magnitude may be expressed approximately as a function of $L_{\rm X}/L_{\rm opt}$:

$$B \approx 17.5 + 2.5 \log_{10}(L_{\rm X}/L_{\rm opt}) \text{ mag.} \tag{1}$$

Typical values of $\log_{10}(L_{\rm X}/L_{\rm opt})$ for various source populations are: for stars, -1 or less; for galaxies, -0.25 or less; for AGN and quasars, -1 to $+1$; and for white dwarfs and X-ray binaries, $+1$ to $+3$ (in extreme cases). At the limit defined by the X-ray binaries, $B \approx 25$ mag, the counterparts will not be present in the POSS images, and ground-based spectroscopy will require 8-m class telescopes, but these cases are expected to be relatively rare. Moreover, within regions covered to the deeper limits of the Sloan Digital Sky Survey (SDSS; York et al. 2000) even X-ray binary counterparts may be detected in reasonable numbers.

The only known optically-inaccessible source population consists of the isolated neutron stars (INSs), which have $L_{\rm X}/L_{\rm opt} \sim 10^5$ (Walter & Matthews 1997; Treves et al. 2000; Kaspi et al. 2004) and are therefore too faint for optical spectroscopy with any current facilities. However, these sources are interesting in their own right: the INSs have been subject to intensive observation – including more than a megasecond of high-spectral resolution observations with *Chandra* and *XMM* – as they are promising test-beds for theories of neutron star (NS) atmospheres, NS structure, the properties of bulk matter at super-nuclear densities, strong-field gravity, and (depending on their intrinsic magnetic field strengths) strong-magnetic field quantum electrodynamical effects.

Given the relatively bright X-ray fluxes of the seven INSs that are known, many more should be present in the BSC down to the survey threshold (Fig. 1). But the relatively large BSC positional uncertainties mean that optically-bright objects may be found with high probability in every error circle: USNO-A2, down to $B \sim 19$, has roughly 10 optical objects in each typical $60''$-diameter (2-sigma) region. Candidate INSs, which should be apparent as BSC sources without likely optical counterparts, are therefore hard to identify.

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[2]USNO star catalogs web site: `http://ftp.nofs.navy.mil/projects/pmm/catalogs.html`

[3]DPOSS web site: `http://dposs.caltech.edu/`

This same confusion problem has prevented the routine identification of BSC optical counterparts even though – as we have seen – most of those counterparts already exist in current optical survey catalogs. Refining the BSC positions to $<5''$ precision, however – a factor of $\approx$3 improvement over the BSC – will provide a factor of $\approx$10 improvement in the two-dimensional localization, reducing the average number of USNO-A2 objects per 2-sigma localization from 10 to one, and thus enabling unique optical identification in nearly every case.

In short, for each $<5''$ BSC source position, either a high-likelihood optical counterpart will be apparent, or the source will be an immediate candidate high-$L_{\rm X}/L_{\rm opt}$ object, that is, a likely X-ray binary or INS.

The systematic identification of the BSC optical counterparts will, in turn, realize the potential of the BSC as a multiwavelength catalog. The USNO-A2 and DPOSS will provide *BRI* color information for the sources, and the 2MASS catalog[4] will provide JHK_s color information. Comparison to the large-area NVSS and FIRST radio surveys will allow identification of radio sources. And finally, the identification of the optical counterparts will enable ground-based spectroscopic studies of the sources, most of which will be accessible to 4-m class facilities.

2.2. Past and Present Efforts

BSC follow-up efforts to-date, although extensive, have ultimately yielded firm identifications for only a minority of the BSC sources. The Hamburg/RASS Catalog (HRC; Zickgraf et al. 2003) contains suggested identifications for 4388 BSC sources based on examination of digitized direct and objective-prism Schmidt plates covering approximately 10,000 deg^2 of the Northern sky, excluding regions within 30° of the Galactic plane. This represents an identification rate of 82% for the 5341 BSC sources in the region; however, the contamination rate of the catalog – the number of proposed counterparts which are actually misidentifications – is not well known. Bade et al. (1998) have estimated a contamination rate of 2% for a preliminary version of the survey; however, a quantitative basis for this estimate is not given, and it seems likely to be an underestimate. Indeed, since the catalog method is to identify each BSC source with its most plausible optical counterpart within $30''$ – based on a priori expectations of the properties of various X-ray emitting source populations – the identification of new or unusual source types is nearly excluded by definition.

[4]2MASS web site: `http://www.ipac.caltech.edu/2mass/`

The *ROSAT* Bright Survey (RBS; Fischer et al. 1998; Schwope et al. 2000) has pursued optical identifications for the bright portions of the BSC ($> 0.2\,\mathrm{c\ s^{-1}}$), also excluding regions within 30° of the Galactic plane; to date they have achieved a 99.5% identification rate for approximately 2000 BSC sources. Again, the contamination fraction is not known. Two known INS sources, RX J1308.6+2127 and RX J1605.3+3249, were discovered in the RBS as BSC sources without bright optical counterparts (Schwope et al. 1999; Motch et al. 1999).

As part of the ongoing Sloan Digital Sky Survey, a component RASS/SDSS survey (Anderson et al. 2003) will be taking spectra of roughly 10,000 candidate counterparts to RASS sources drawn from the BSC and its companion Faint Source Catalog (FSC; Voges et al. 2000). Sources in the Sloan survey region, with detection likelihoods of more than 10 in either the BSC or FSC, will be targeted with (on average) one spectroscopic fiber per source, placed on a single candidate optical counterpart brighter than the SDSS spectroscopic limit (g, r, or $i < 20.5$ mag). This approach, combined with standard SDSS 5-color quasar selections, has proved efficient at identifying likely X-ray luminous AGN (Anderson et al. 2003); at the same time, it cannot address the properties of the optically fainter populations in the BSC.

Finally, during the lifetime of the *ROSAT* mission itself, a number of HRI surveys of BSC targets, selected by various metrics, were carried out. The aim of these surveys was typically to improve the source positions, and/or resolve the sources themselves, with higher-resolution HRI imaging; since the HRI is less sensitive than the PSPC, pointed observations of at least 1 ks exposure time are required for these purposes. In all, such HRI pointings provide coverage for 9.1% of the BSC sources, and the varying motivations for the surveys makes this subset of BSC source identifications a somewhat motley one.

Rutledge et al. (2003) investigated the prospects for BSC source identification using statistical techniques of catalog cross-correlation (see also Rutledge et al. 2000). In particular, they compared the BSC to the USNO-A2, IRAS point-source, and NVSS catalogs, and carried out follow-up observations of candidate high-$L_{\mathrm{X}}/L_{\mathrm{opt/IR/radio}}$ sources with the *Chandra* HRC and ground-based telescopes, with the aim of either discovering new INSs or setting stringent limits on their frequency within the BSC. Although they find no new INSs, they "rediscover" two: with a high probability of having no counterpart in the off-band catalogs, these two are selected as part of the authors' original 32-candidate sample. Moreover, by applying their selection to a group of artificial test sources, they show that their sample is subject to an 80% confusion rate: 80% of isotropically-distributed sources without off-band counterparts are nonetheless associated with a nearby, bright optical object with modest (<90%) confidence. Naturally, this is most commonly true of sources in the Galactic plane, where the density of USNO-A2 objects is highest.

Perhaps more importantly, Rutledge et al. (2003) find that all 12 of the X-ray sources for which they are able to determine refined positions, either from *Chandra* HRC (sub-arcsec) or *ROSAT* HRI ($\sim$3 arcsec) observations – and none of which are INSs – are associated with objects from the USNO-A2 optical and/or 2MASS near-infrared (NIR) catalogs. Thus, they conclude that the identification of off-band counterparts to BSC sources can be seen as limited strictly by the absence of higher-quality X-ray positions, rather than by high X-ray to optical/NIR flux ratios. This confirms the argument we have made by reasoning from the $L_{\rm X}/L_{\rm opt}$ properties of known source populations: given the X-ray flux limit of the BSC, the existence of off-band counterparts in archival surveys can be expected, for all known source populations except the X-ray binaries and INSs.

2.3. Complete BSC Identification

Identifications of the BSC sources, as a class, are worth pursuing. The very brightness of these brightest soft X-ray sources makes them interesting, since they can easily be made the subject of high signal-to-noise follow-up observations with *Chandra*, *XMM*, and future high-energy missions such as *Constellation-X*. In particular, any object at the BSC threshold (depending on the source spectrum) will yield 3000 to 6000 or 1500 to 3000 counts in the dispersed spectrum of a 100-ks exposure with the *XMM* or *Chandra* gratings, respectively, and count rates of $\approx$0.7 c s^{-1} (*XMM* EPIC PN) or $\approx$0.15 c s^{-1} (*Chandra* ACIS-S) in the main CCD detectors of those missions.

The large-scale efforts that have already been devoted to optical follow-up and identification of BSC sources, discussed above, testify to the intense interest in establishing optical counterparts to these sources. Improved positions for BSC sources will greatly assist these efforts, providing the impetus that is probably necessary to drive them forward to an ultimate completion level of $\gtrsim$90%. Efforts to-date have focused primarily on the bright end of the BSC and away from the Galactic plane, and with good reason – at fainter flux levels and nearer the plane confusion problems for the BSC positions are severe. Only improved positions from X-ray observations can alleviate this difficulty.

Achieving a substantial completion fraction for BSC source identifications is the best means to enumerate in full the rare source populations of the BSC and identify new source populations if they exist. The large-area surveys of the BSC have been biased towards discovery of optically bright or emission-line sources associated with X-ray bright BSC sources outside of the plane of the Galaxy ($|b| > 30°$). This focus on high Galactic latitudes presents a particular problem for Galactic populations, which can be expected to prefer the plane of the Galaxy: such populations will be subject to greater confusion in general and, in addi-

tion, will have had a large fraction of their population – all those members within 30° of the plane – skipped entirely by most follow-up efforts. Apart from the INSs, such populations could include, for example, low-mass X-ray binary systems (LMXBs) in quiescence, and Bondi-accreting isolated black holes, the higher-mass counterparts to the INS population.

The discovery of sources in new or rare extragalactic populations is also a possibility. For the most part, the BSC surveys have operated under the presumption that any AGN within a BSC error circle is necessarily a BSC source counterpart. While the estimated sky density of AGN is low enough to make this approach reasonable in the aggregate, without any quantitative estimate of the likelihood of each association, contamination of the resulting sample is guaranteed. In each case where such a mistaken BSC-AGN association has been made, we will find instead a non-X-ray luminous AGN, on the one-hand, and a BSC source without prominent AGN counterpart, on the other. The latter class of BSC sources may well yield new types of extragalactic X-ray sources.

Finally, as we discuss further in the sections that follow, there are good reasons to perform BSC follow-up with *Swift*. In addition to providing improved positions for the BSC sources, a 500-s observation with the XRT and UVOT will provide new spectral information in the 0.2–10 keV X-ray band and in the optical or UV (200 to 600 nm), depending on the choice of UVOT filter. Since the BSC sources are prominent in the soft X-ray band, they are an exclusively low-extinction population, and the UV data – which cannot be gathered by ground-based observers – are of particular interest. Whenever possible, one of the UV filters should be in place for BSC observations; it is not clear if this will be possible, however, in every case (§4.3).

3. Observational Strategy

Our proposed observational strategy is straightforward. Since the *Swift* XRT and *ROSAT* PSPC have comparable sensitivity and overlapping spectral ranges (Table 1), a broad range of spectra produce comparable count rates in the two instruments. In particular, for a given PSPC count rate, very soft spectra produce fewer counts in the XRT, and very hard or extinguished spectra produce many more counts in the XRT.

We therefore choose a standard 500-s exposure per source. This will suffice to collect ∼25 counts from sources near the 0.05 c s^{-1} threshold of the BSC which have not faded substantially from their *ROSAT*-era flux level. Detection of 25 counts will provide a detection with high confidence, and allow a localization with a purely statistical precision of 1.5-arcsec (radius, 1-sigma). It is anticipated that the absolute pointing of the XRT, relative

to the UVOT, will be subject to systematic uncertainties at the 3-arcsec level; however, it is possible that experience with satellite operations on-orbit will eventually reduce this systematic uncertainty to less than 1 arcsec.

Figure 2 illustrates the two-dimensional distribution of BSC sources in PSPC count rate and localization uncertainty (radius, 1-sigma). Under the assumption of count-rate parity with the *Swift* XRT, it also shows the expected positional uncertainties from our standard 500-s exposure, both with and without the 3-arcsec contribution from the XRT absolute pointing uncertainty. As the figure demonstrates, BSC sources that have more or less maintained their *ROSAT*-era X-ray luminosity will be localized with 10 to 30 times better two-dimensional precision than in the BSC.

These uncertainty calculations will be rendered academic in cases where a counterpart can be identified (and hence localized to sub-arcsec precision) in the simultaneous UVOT exposure, which will have a limiting magnitude of $B = 23.5$ mag for the B band, and a comparable limit for other filters when they are used. Since BSC source positions are already subject to confusion at the limit of the USNO-A2 catalog and corresponding archival optical surveys, the identification of a high-likelihood counterpart from UVOT imaging alone will be most probable in cases where a UV or far-UV filter is used, since this will help to distinguish the BSC sources from the field.

In other cases, a UVOT identification may follow from the refined localization derived from the XRT data. The potential for this type of "localization cascade," deriving from a single pointed observation with a single satellite mission, is a unique but not accidental capability of *Swift*, which was designed to produce this cascade routinely in the course of its rapid-response GRB follow-up observations.

Survey observations are not time-sensitive, so given the rapid one degree per second slew rate of the *Swift* spacecraft, the scheduling of the Swift-BCS should not present significant operational challenges. For example, if we demand a duty cycle of $\gtrsim$90% for survey operations, then we are restricted to slewing, on average, less than 25° before and after each BSC target. This should not be a difficult requirement to meet; smaller average slews can probably be achieved with optimization of the planning software.

4. *Swift* Operations and the Swift-BSCS

The current plan for *Swift* operations on-orbit is summarized in the Technical Appendix to the announcement and call for proposals for the *Swift* Cycle 1 Guest Investigator Pro-

gram.[5] The satellite will be launched into a 22°-inclination low-Earth orbit, and given the pointing restrictions of the BAT, XRT, and UVOT instruments, there will be no "continuous viewing zone." Rather, any given position on the sky will be excluded from view for some or most of each 95-minute orbit. As a result – and taking advantage of the satellite's slewing capabilities – each orbit will be divided into 4 to 6 distinct 10-min to 20-min pointings, each scheduled during an appropriate visibility window. In this manner the satellite instruments will never suffer from Earth occultation, and a high duty cycle for the mission can be achieved. Protective measures for the XRT and UVOT during passage through the South Atlantic Anomaly should represent the only substantial recurring interruptions; even data that are taken during satellite slews by the BAT and XRT instruments will be amenable to later analysis.

4.1. Relation to Primary Science

Through at least its first 1.5 years on-orbit, and quite possibly beyond, *Swift* will be committed to the follow-up of every GRB it detects, from the moment of trigger until the GRB has faded below detectability to the XRT and UVOT. This is expected to last one to two weeks in the average case, although for rare, bright, low-redshift events (e.g. GRB 030329; Price et al. 2003; Lipkin et al. 2003) it could last for months. The amount of time devoted to GRB follow-up, then, depends on the expected trigger rate from the BAT.

Current estimates for this rate are in the range of 100 to 150 GRBs per year. Assuming *Swift* observation of five targets per orbit, and ten days of follow-up observations per burst, this range of trigger rates corresponds to a commitment of 55% to 82% of the total time on-orbit. The remainder of the on-orbit time will necessarily be devoted to observations of non-afterglow targets.

The use of 10% of the time on-orbit for the Swift-BCS thus seems likely to be consistent with the primary GRB mission of *Swift*. The individual 500-s pointings will be easy to fit into the typical 20-min visibility window for a single orbit; on average the Swift-BCS will contribute one target per orbit to the *Swift* schedule. When new GRBs are detected, the automated flight software will override the preplanned observations and initiate a standard GRB observations sequence, including follow-up observations in subsequent orbits. Since the Swift-BCS preplanned targets will always be of lower priority than new GRBs and active afterglows, the execution of the survey will at no point conflict with the GRB primary mission.

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[5]See `http://swiftsc.gsfc.nasa.gov/docs/swift/proposals/cycle1_gi.html`

4.2. Relation to Secondary Science

Execution of the Swift-BCS is also consistent with the mission's secondary science goals. The most important non-GRB science goals of *Swift* relate to the proposed all-sky surveys with the BAT instrument. Two survey components are planned: On a daily basis, the BAT will be used to monitor the full sky down to source fluxes of $\gtrsim$20 mCrab (10–100 keV); and over the course of the initial two-year mission, a deep BAT all-sky survey will be conducted, reaching 10–100 keV source fluxes of $\gtrsim$1 mCrab. Both of these surveys will be carried out by the BAT instrument team at Goddard Space Flight Center and Los Alamos National Laboratory. The daily scans will allow the BAT to serve as a hard X-ray "all-sky monitor," alerting the community when a bright new source has appeared or a familiar source has undergone a change of state; the two-year all-sky survey will be $\gtrsim$10 times more sensitive than the only previous such hard X-ray survey, by *HEAO A-4* in 1977-79 (Levine et al. 1984), and should detect hundreds of sources.

Since the BAT has a 1.4 sr field of view (half-coded), carrying out the daily survey in a dedicated fashion would require $\approx$8 pointings, of 600 s exposure each, to tile the accessible sky (given the 45° exclusion cone around the Sun). Some of this BAT survey coverage will be provided by GRB follow-up observations, but at our estimated trigger rates these provide only 3 to 5 active afterglows on any given day. The exact pointings selected to satisfy BAT coverage of the remaining tiling positions will need to be chosen according to some other criterion.

Since BSC sources provide close to uniform coverage of the full sky (Fig. 3), targets at locations complementary to the current GRB follow-up positions can be selected to complete the tiling on each day – the 500-s exposure time of the Swift-BCS is about the same as for the BAT pointings. Observing BSC sources at the appropriate tiling positions would account for 3 to 5 of the 17 BSC targets per day that will be observed for a survey using 10% of the time on-orbit.

4.3. Constraints

There are several operational constraints on the *Swift* mission that will impact its ability to carry out the Swift-BCS as we have described it.

First, the current approved mission lifetime is two years, which is not sufficient to complete the survey at a 10% fraction of the time on-orbit. We consider the chances for a mission extension quite good, however, given the unique capabilities of the satellite and the revolution in GRB studies – including the application of bright afterglows to outstanding

problems in astrophysics and cosmology – that we expect it to bring about. The satellite orbit itself is expected to be stable for at least six years.

Next, changes in the UVOT filter involve moving parts with a finite lifetime, so that it is desirable to minimize these filter changes. Moreover, since the filters are arranged in a wheel with changes happening in strict sequence, changes should preferentially be made in this order. During GRB follow-up observations, the six broadband filters (and for bright bursts, the grisms) will be stepped through in strict succession, with roughly equal exposure times per filter. At early times, filter changes will happen several times per visibility window, while at late times, each visibility window will be devoted to observations in a single filter.

Since survey operations are of lower priority than afterglow observations, we cannot expect to have free access to any particular UVOT filter for any observation. For this reason, we have avoided assuming that the BSC sources will be observed uniformly in a single filter, even though this would be the obvious preference for any complete survey. Moreover, in the case of the Swift-BCS, we have a scientific preference for UV rather than optical observations: the target BSC sources are bright and unextinguished, and likely to have relatively bright UV emission; in addition, UV observations represent a distinctive capability of *Swift*, while optical observations can be made from the ground. The ultimate allocation of filter changes for the survey will thus represent a compromise between survey science and satellite operations.

Next, given the satellite power constraints there is an approximate 500 degree per orbit slew limit. In general the current operations plan, which specifies 4 to 6 pointings per orbit to satisfy visibility constraints, is not expected to tax this limit. However, the 500-s observations of the Swift-BCS may be considered slightly shorter than optimal, in the sense that they may not fill the window of visibility for the target. Given the ready availability of BSC sources near most sky positions, it seems unlikely that the slew constraint will present a problem for survey operations, and this can be confirmed by simulations of the survey execution on orbit.

We note that with the 23.6-arcmin field of view of the XRT it will be possible in some cases to observe two BSC sources in a single pointing. This represents an opportunity to reduce the total time request for the survey by approximately 10%.

Finally, it is clear that the Swift-BCS cannot be carried out without full support and close interaction with the *Swift* team. In a pragmatic sense, no such additional, large-scale project can be contemplated without added moneys to support the activity. We have restricted ourselves to the scientific case for the Swift-BCS; eventually, budgetary resources will also have to be secured.

5. Conclusions

We have investigated the prospects for a complete survey of the 18,811 sources of the *ROSAT* All-Sky Survey Bright Source Catalog (BSC) with the *Swift* gamma-ray burst satellite, the "Swift-BCS," and find them to be good. With 10% of the time on-orbit, over a three-year period, each BSC source can be observed for 500 s with the satellite's narrow-field X-ray (XRT) and UV/Optical (UVOT) telescopes. The XRT observation will provide an improved <5-arcsec position for every BSC source that has not faded by more than a factor of 5 from its *ROSAT*-era flux level, and in addition, provide a 0.2–10 keV flux for the source. The localization will represent an improvement by a factor of 10 to 30 in two-dimensional precision over the BSC positions (Fig. 2). The simultaneous UVOT observation, taken in one of six broadband filters in the 200 nm to 600 nm wavelength range, will reach a limiting magnitude of $B = 23.5$ mag or its rough equivalent, yielding candidate UV/optical counterparts or deep limits in every case.

Given the brightness of the BSC sources, and the $L_{\rm X}/L_{\rm opt}$ properties of known source populations, the improved positions of the Swift-BCS can be expected to yield counterpart identifications in the great majority of cases. Indeed, Swift-BCS sources without plausible optical (USNO-A2 or UVOT) counterparts will be immediate candidate X-ray binaries or isolated neutron stars (INSs; Fig 1).

Deriving counterpart identifications for the great majority of BSC sources will realize the promise of the BSC as a multiwavelength catalog, and is the best means to enumerate the rare source populations in the BSC and discover any new populations that may exist. Without improved positions these efforts will continue to be frustrated by confusion problems – with multiple USNO-A2 sources in the typical $60''$-diameter 2-sigma error circle, establishing a unique identification is nontrivial (Rutledge et al. 2000, 2003) – and affected by unknown levels of contamination – most efforts have associated each BSC source with the most promising candidate in its error circle, without deriving a quantitative estimate of the likelihood of association. Each counterpart identification, then, will enable flux estimates or upper limits across the electromagnetic spectrum via current optical (DSS, DPOSS, SDSS), near-infrared (2MASS), and radio (NVSS, FIRST) surveys.

Any interesting BSC source that can be identified in this manner will be readily accessible to high signal-to-noise, high-resolution X-ray spectroscopy by *XMM-Newton* and *Chandra*. In addition, those sources with optical counterparts will for the most part be accessible to optical-spectroscopic studies from modest-sized (4-m class) ground-based facilities.

We have investigated *Swift* mission constraints on the Swift-BCS and do not find them

to be severe. The BSC targets will be of lower priority than new GRBs or active GRB afterglows, so that the survey will not conflict with the primary *Swift* goal of GRB observations. Moreover, the Swift-BCS observations can be scheduled so as to advance the secondary science goals of a daily all-sky hard X-ray (10–100 keV) survey to $\gtrsim$20 mCrab, and a two-year all-sky survey to $\gtrsim$1 mCrab, executed with the wide-field Burst Alert Telescope (BAT). The 10% commitment of satellite time corresponds to roughly one BSC target per 95-min orbit. Each such orbit will typically involve observations at 4 to 6 distinct pointings, some 3 to 5 of which will be active GRB afterglows.

Execution of the Swift-BCS will surely represent an operational challenge for the mission. The progress of the survey will have to be monitored on an orbit by orbit basis, with new targets chosen from the unobserved portions of the BSC, and target lists updated as necessary when new GRB triggers result in the automated rescheduling of satellite observations. Moreover, some level of global optimization of target choices will be desired, to retain isotropy of the remaining targets, as much as possible, until the very end of the survey.

However, the resulting capability for routine observations of large numbers of distinct targets will prove valuable should the *Swift* team choose to pursue complete surveys of other target catalogs. In particular, the positions of sources identified in the two-year BAT all-sky survey will only be known to few-arcmin precision, so that a uniform campaign of follow-up observations with the XRT might be worth considering. Complete XRT+UVOT surveys of other target populations – for example, targets from the forthcoming *GALEX* all-sky imaging survey – might also be contemplated. Execution of these or similar projects will require a capability like that needed for the Swift-BCS.

Ultimately, the choice to pursue the Swift-BCS is a choice to pursue the science we have described in preference to other non-GRB observations that *Swift* might carry out. Beyond the first 1.5 years of on-orbit operations, the *Swift* Guest Investigator program will enter Cycle 2, and may solicit proposals from the community for pointed XRT and UVOT observations of designated non-GRB targets. Continued execution of the Swift-BCS into this era would imply that less time would be available for these programs, for two or three cycles, until the Swift-BCS is completed.

In a generic sense, the choice to make short observations of a large number of targets, as we propose here, may be contrasted with the alternative of making deeper exposures of some smaller set of targets, for example, monitoring X-ray binaries, soft gamma-ray repeaters, anomalous X-ray pulsars, or selected X-ray bright AGN at regular intervals. The variety of science which might be accomplished with such campaigns is surely rich, and beyond our capability to summarize or even hint at in this context. However, we believe that the science gains of a complete Swift-BCS are of sufficient value to warrant at least a similar level of

consideration.

Most importantly, the science of the Swift-BCS is science that only *Swift* can achieve. *Swift*'s combination of multiwavelength instrumentation, fast-slew capability, and flexibility in target scheduling make it the only present or planned satellite mission capable of executing a complete BSC survey without significant operational overheads. The Swift-BCS thus represents the best opportunity for many years to come to expand the number of securely-identified X-ray sources by an order of magnitude, from ∼2000 to ∼18,000. Declining to take advantage of this opportunity will restrict the observations of the current and next-generation X-ray missions to more or less the known population of X-ray sources that exists today. On the other hand, prompt execution of the Swift-BCS will allow immediate follow-up studies with *XMM* and *Chandra* of the most intriguing new members of all X-ray source populations, from stars to compact objects to AGN. This will renew the promise of these observatories, for all areas of X-ray astronomy, as they enter their extended mission phase.

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Property	PSPC	Swift
Effective Area (cm^2)	150	135
Energy range (keV)	0.1–2.4	0.2–10.0
PSF FWHM (arcsec)	25.0	18.0
$E/\Delta E$	2.5	$\gtrsim$10

Table 1: Basic properties of the *ROSAT* PSPC and *Swift* XRT.

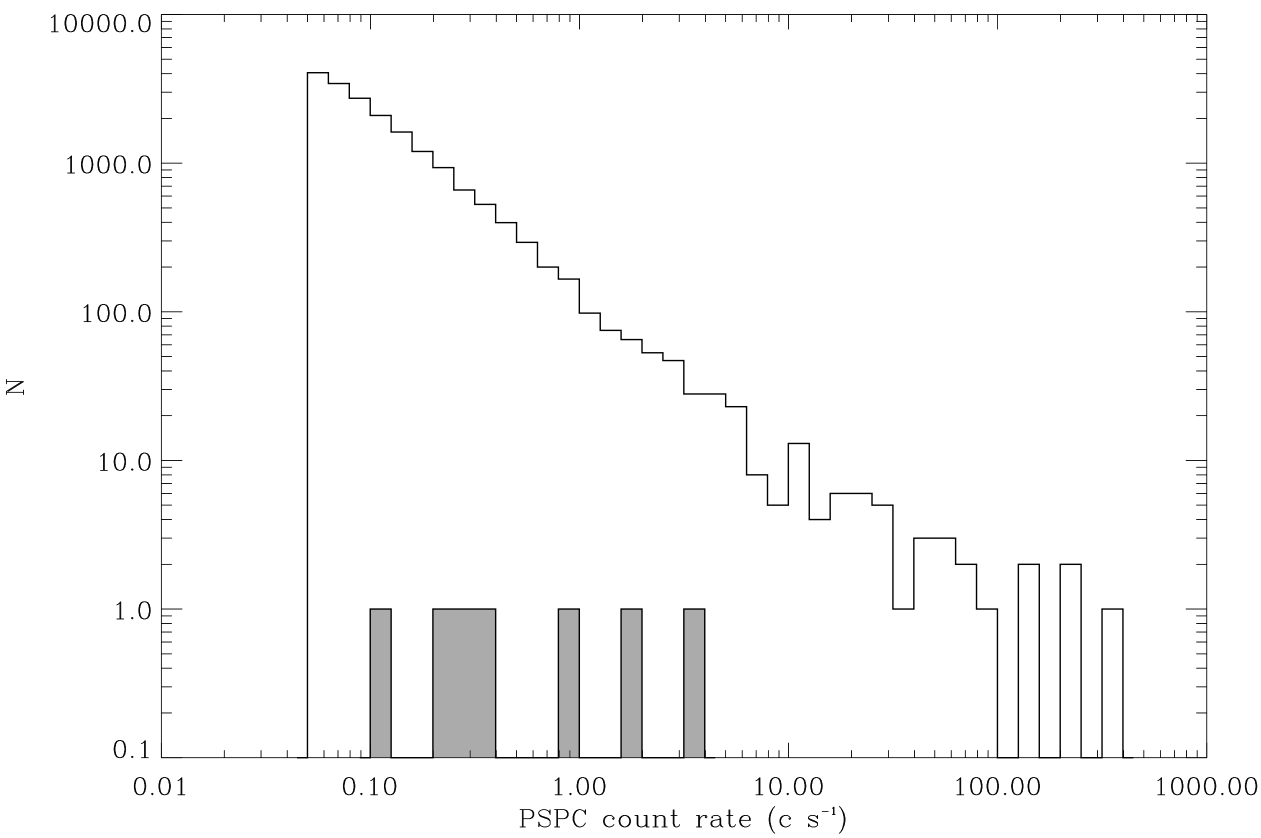

Fig. 1.— *ROSAT* BSC source luminosity function, and comparison to the known population of isolated neutron stars (shaded histogram; Treves et al. 2000; Kaspi et al. 2004). With the vast majority of BSC sources unidentified, many INS sources may be present within the fainter portions of the BSC. Note that the power-law slope of the luminosity function at low count rates is $\alpha = -1.23$.

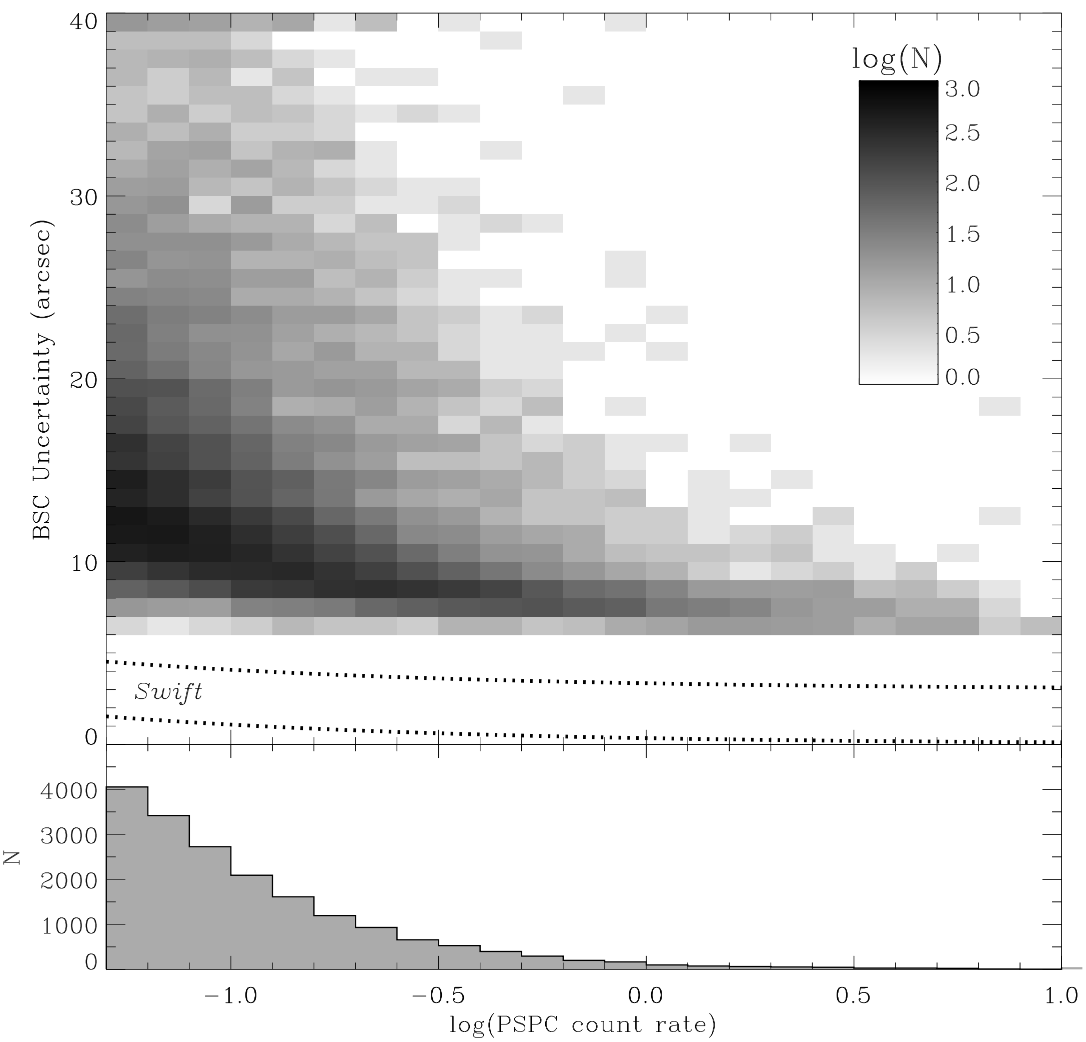

Fig. 2.— Distribution of *ROSAT* BSC sources in count rate and positional uncertainty. Top panel: Two-dimensional histogram of BSC sources as a function of count rate and positional uncertainty, represented in grayscale (note the logarithmic stretch). Approximate *Swift* XRT uncertainties (500 s exposure) as a function of source count rate are indicated by the dotted lines; the lower line indicates the statistical uncertainty only, with the upper line including an estimated 3-arcsec systematic uncertainty. Most classes of source are expected to yield roughly equal count rates in the XRT and PSPC. Bottom panel: One-dimensional histogram of BSC sources as a function of count rate. For the great majority of BSC sources, a *Swift* XRT snapshot will improve the position determination by a factor of 3 to 4 in diameter and 10 to 15 in area.

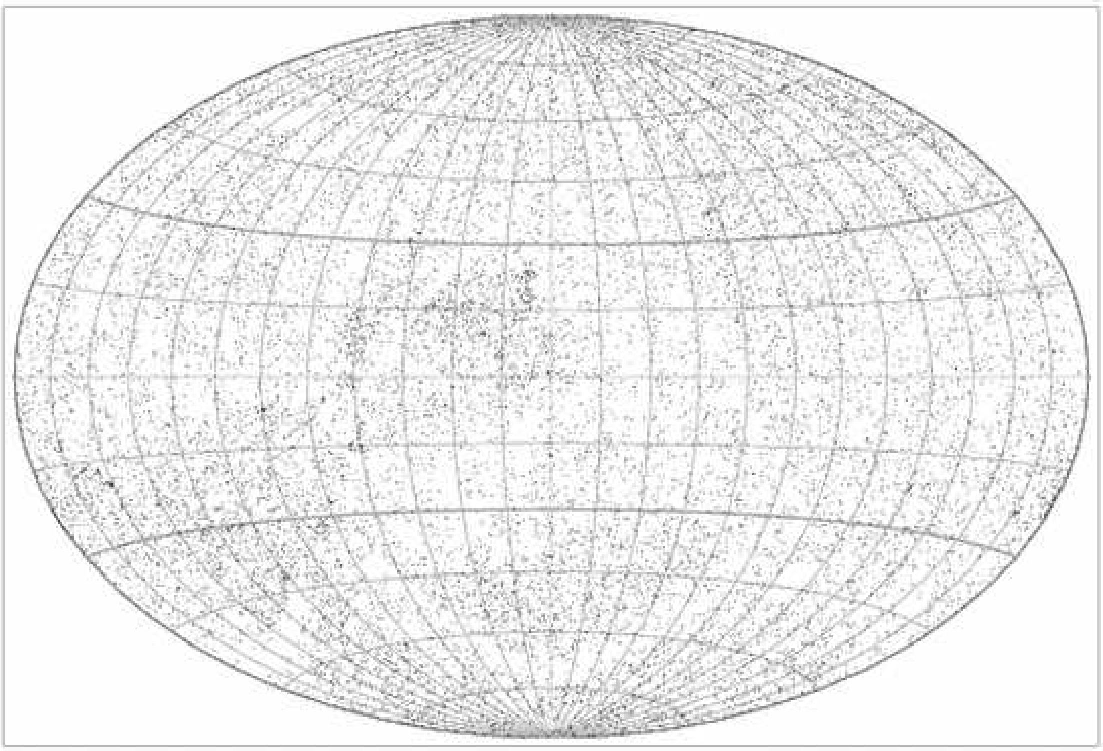

Fig. 3.— Distribution of BSC sources in Galactic coordinates; Galactic longitude $l = 0°$ at the center and increases to the right. The catalog is complete over 92% of the sky, with some gaps in coverage due to the (ecliptic-oriented) scan pattern of the *ROSAT* All-Sky Survey (see Voges et al. 1999). Lines of Galactic latitude $|b| = 30°$ are highlighted; these are the limits of the large-area optical surveys for BSC counterparts that have been carried out to date, which exclude the Galactic plane; see §2.2 for details.